

**LEPTOQUARK AND  $R$ -PARITY VIOLATING SUSY PROCESSES <sup>a</sup>**

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Pair production of leptoquarks at future  $e^+e^-$  linear colliders is investigated for center-of-mass energies of 500 GeV and 800 GeV and an integrated luminosity of 500 fb<sup>-1</sup>. Based on a Monte Carlo simulation we estimate the event rates for signal as well as background processes and evaluate the discovery potential. As an example of virtual effects we consider deviations from standard model predictions due to  $R$ -parity violating sneutrino exchange in purely leptonic processes.

**1 Introduction**

If leptoquarks (LQ) exist with sufficiently low masses, they would affect measurements at present and future colliders in many ways. In electron-positron collisions they may be produced in pairs or as single particles, while virtual LQ exchange may show up in  $e^+e^- \rightarrow$  hadrons. In this study, we update a previous investigation<sup>1</sup> of LQ pair production focussing on the possibility of an integrated luminosity as high as 500 fb<sup>-1</sup>, while in Ref.<sup>1</sup> much lower luminosities, 20 fb<sup>-1</sup> at the center-of-mass energy  $\sqrt{s} = 500$  GeV and 50 fb<sup>-1</sup> at  $\sqrt{s} = 800$  GeV are considered.

Specifically, in SUSY models with  $R$ -parity violating Yukawa couplings one can have processes of the above kind with squarks playing the role of leptoquarks. Moreover, pair or single production of sleptons and slepton exchange can give rise to purely leptonic processes. Here, we illustrate the impact of virtual effects for the case of sneutrino exchange in  $e^+e^- \rightarrow l^+l^-$  where  $l = e, \mu, \tau$  investigated previously for LEP2<sup>2</sup>.

References to related work in the literature can be found in Ref.<sup>1,2</sup>.

**2 LQ Pair Production**

The general theoretical framework of LQ quantum numbers and couplings is described in Ref.<sup>3,4</sup>. Following the usual procedure we assume that only a single multiplet of mass degenerate leptoquarks is present at a time and that these decay only into standard model leptons and quarks. Furthermore, we restrict ourselves to leptoquarks of the first generation decaying into  $e^\pm$  or  $\nu_e$  plus a jet. In lowest order, LQ pairs are produced in  $e^+e^-$  annihilation via  $\gamma$  and  $Z$  exchange (Fig. 1a) and via quark exchange (Fig. 1b). In the first case, the amplitude is determined by LQ gauge couplings, i.e. their electric charge and weak isospin, whereas the second case involves LQ-lepton-quark Yukawa couplings  $\lambda$ . Experimental constraints<sup>5</sup> require the latter to be approximately chiral. At  $\sqrt{s} = 500$  GeV and for negligible  $\lambda$ , the production cross sections<sup>1</sup> range from 6 – 150 fb for scalar leptoquarks of mass

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$m_{LQ} = 200$  GeV and from  $0.2 - 1.8$  pb for vector leptoquarks. Beamsstrahlung and initial state radiation are included in these estimates.

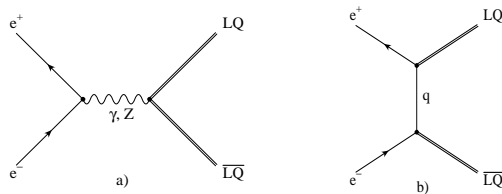


Figure 1: LQ pair production in  $e^+e^-$  colliders at lowest order.

## 2.1 Monte Carlo simulation

We have performed a detailed Monte Carlo study based on the event generator **LQPAIR**<sup>6</sup> with the lowest order matrix elements are taken from Ref.<sup>4</sup> and corrected for beamstrahlung and initial state radiation. Hadronic final states are generated by an interface to the LUND Monte Carlo programs for jet fragmentation. In the event analysis we have used the Durham jet algorithm. Finally, an interface to the program **SMEAR**<sup>7</sup> allows for a realistic detector simulation.

The LQ decays give rise to three different event topologies called I to III in Table 1 without/with missing momentum  $p^{\text{miss}}$  carried away by neutrinos. For clean event identification and precise mass reconstruction, cuts on energies and transverse momenta have to be applied. The most relevant of them are given in Table 1. For further details we refer to Ref.<sup>1</sup>.

variable	(I) $e^+e^- + 2$ jets	(II) $e^\pm + 2$ jets $+p^{\text{miss}}$	(III) 2 jets $+p^{\text{miss}}$
$p_T^e$	$\geq 20$ GeV	$\geq 20$ GeV	$\geq 20$ GeV veto
$p_T^{\text{miss}}$	$\leq 25$ GeV	$\geq 25$ GeV	$\geq 25$ GeV
$E_j$	$\geq 10$ GeV	$\geq 10$ GeV	–
$E_{\text{vis}}$	$\geq 0.9\sqrt{s}$	$\geq 0.6\sqrt{s}$	–
$p_T^j$	–	–	$\geq 75$ GeV
$E_{\text{had}}$	–	$\geq 150$ GeV	$\leq 300$ GeV

Table 1: General cuts used for event identification.

## 2.2 Background Processes

The dominant standard model background is due to vector boson pair production,  $e^+e^- \rightarrow ZZ, W^+W^-$ , with one  $Z$  or  $W$  decaying leptonically and the other one decaying into two jets. This background is simulated with the help of **WPHACT**<sup>8</sup> including single- and non-resonant four-fermion production. Another significant source for signal contamination is top quark production,  $e^+e^- \rightarrow t\bar{t}$ , followed by  $t \rightarrow bW$ , with the  $W$  decaying leptonically. In order to suppress the above background the following additional cuts are applied<sup>1</sup>:

$$|M_{\ell_1\ell_2} - M_{Z,W}| \geq 10 \text{ GeV (I), } 20 \text{ GeV (II,III),}$$

$$|M_{j_1 j_2} - M_{Z,W}| \geq 10 \text{ GeV (I), } 20 \text{ GeV (II,III),}$$

$$M_{\ell_1 \ell_2}, M_{\ell_1 j_2}, M_{j_1 \ell_2} \geq 20 \text{ GeV (I,II), } M_{j_1 j_2} \leq 400 \text{ GeV (III).}$$

The indices  $j_1$  and  $j_2$  label the two jets ordered by their energies such that  $E_{j_1} > E_{j_2}$ , whereas  $\ell_1$  and  $\ell_2$  label the leptons ordered by  $|M_{\ell_1 j_1} - M_{\ell_2 j_2}| < |M_{\ell_1 j_2} - M_{\ell_2 j_1}|$ .

The number of background events in channel (I) to (III) surviving the above cuts at  $\sqrt{s} = 500$  (800) GeV and  $500 \text{ fb}^{-1}$  integrated luminosity is obtained from Table 5 of Ref. <sup>1</sup> after multiplication by factors of 25 (10) for  $\sqrt{s} = 500$  (800) GeV to account for the higher luminosity. Similarly, one can infer the number of LQ events expected for  $500 \text{ fb}^{-1}$  after cuts from the corresponding numbers for  $20 \text{ fb}^{-1}$  and  $50 \text{ fb}^{-1}$ , respectively, given in Table 6 of Ref. <sup>1</sup>. There the rates in channel (I) and (II) are compared for the vector ( $V_0$ ) and scalar ( $S_0$ ) states with the least favourable production cross sections, and for two collider energies choosing  $m_{LQ} \approx 0.9\sqrt{s}$ . For channel (I), results are also given for  $V_1$  and  $S_1$  having the largest production cross sections among the vector and scalar states, respectively. The apparent strong dependence of the event rates on the LQ quantum numbers together with a mass measurement should allow for an efficient discrimination of different LQ hypotheses.

### 2.3 Sensitivity limits

A rough estimate of the sensitivity limits can be based on the total number of events. To that end we determine the range of leptoquark masses, for which the number of signal events is equal to or larger than five times the number  $N_{bg}$  of background events. The upper limits of these mass ranges are summarized in Table 2 together with the expectation for the lower luminosities assumed in Ref. <sup>1</sup>. Note that the background in channel I is approximately 10 (200) times smaller than the background in channel II (III).

Accepting the requirement of a  $5\sigma$  effect as a sensible discovery criterion, one finds that at  $\sqrt{s} = 500$  (800) GeV and with  $500 \text{ fb}^{-1}$ , scalar leptoquarks can be discovered for masses up to 86–98% (50–99%) of  $\sqrt{s}/2$ , while vector states should be observable for masses up to 97–99% (86–99%) of  $\sqrt{s}/2$ . The corresponding mass limits for  $\sqrt{s} = 500$  GeV and  $20 \text{ fb}^{-1}$  ( $\sqrt{s} = 800$  GeV and  $50 \text{ fb}^{-1}$ ) are 73–98% (37–97%) of  $\sqrt{s}/2$  for scalars, and 94–99% (82–99%) of  $\sqrt{s}/2$  for vectors. The higher luminosity thus helps to increase the mass reach in the case of scalar leptoquarks with less favourable quantum numbers by about  $(0.1 \text{ to } 0.2) \sqrt{s}/2$ . In particular, the species  $^{-1/3}S_0$  and  $^{-1/3}S_1$  which are unobservable in channel II for the lower luminosities and for masses above 100 GeV can be probed with the high luminosity in an interesting mass range. The same holds for  $^{-2/3}S_{1/2}$  in channel III at  $\sqrt{s} = 800$  GeV.

## 3 Sneutrino Exchange

The  $R$ -parity violating term  $\frac{1}{2}\lambda_{ijk}L_iL_jE_k^c$  in the superpotential, where  $L_i$  and  $E_k$  denote left-handed doublets and right-handed singlets of lepton superfields and  $i, j, k$  are generation indices, induces new contributions to  $e^+e^- \rightarrow l^+l^-$  from virtual sneutrino exchange as shown in Fig. 2.

A: $\sqrt{s} = 500\text{GeV}$ , (20 fb $^{-1}$ ) 500 fb $^{-1}$							
search		I		II		III	
$5\sqrt{N_{bg}}$		(18)	90	(61)	306	(251)	1259
states	$B_{eq}$	mass reach in GeV					
$-1/3\tilde{S}_0$	$2/3$	(202)	<b>228</b>	( $\diamond$ )	<b>205</b>	( $\diamond$ )	$\diamond$
	$1/2$	(183)	<b>220</b>	( $\diamond$ )	<b>208</b>	( $\diamond$ )	$\diamond$
	1	(217)	235	(-)	-	(-)	-
$-4/3\tilde{S}_0$	1	(242)	245	(-)	-	(-)	-
$2/3\tilde{S}_1$	0	(-)	-	(-)	-	(225)	238
$-1/3\tilde{S}_1$	$1/2$	(183)	<b>220</b>	( $\diamond$ )	<b>208</b>	( $\diamond$ )	$\diamond$
$-4/3\tilde{S}_1$	1	(244)	245	(-)	-	(-)	-
$-2/3\tilde{S}_{1/2}$	$1/2$	(230)	241	(221)	236	(179)	<b>212</b>
	0	(-)	-	(-)	-	(218)	235
	1	(240)	245	(-)	-	(-)	-
$-5/3\tilde{S}_{1/2}$	1	(244)	245	(-)	-	(-)	-
$1/3\tilde{\tilde{S}}_{1/2}$	0	(-)	-	(-)	-	(198)	214
$-2/3\tilde{\tilde{S}}_{1/2}$	1	(237)	244	(-)	-	(-)	-
$-1/3\tilde{V}_{1/2}$	$1/2$	(241)	244	(237)	242	(220)	237
	0	(-)	-	(-)	-	(236)	242
	1	(245)	246	(-)	-	(-)	-
$-4/3\tilde{V}_{1/2}$	1	(247)	247	(-)	-	(-)	-
$2/3\tilde{\tilde{V}}_{1/2}$	0	(-)	-	(-)	-	(236)	242
$-1/3\tilde{\tilde{V}}_{1/2}$	1	(244)	245	(-)	-	(-)	-
$-2/3\tilde{V}_0$	$2/3$	(241)	244	(233)	241	(195)	<b>220</b>
	$1/2$	(238)	242	(234)	239	(212)	227
	1	(244)	247	(-)	-	(-)	-
$-5/3\tilde{\tilde{V}}_0$	1	(247)	247	(-)	-	(-)	-
$1/3\tilde{V}_1$	0	(-)	-	(-)	-	(241)	245
$-2/3\tilde{V}_1$	$1/2$	(238)	242	(234)	239	(212)	227
$-5/3\tilde{V}_1$	$1/2$	(248)	247	(-)	-	(-)	-

B: $\sqrt{s} = 800\text{GeV}$ , (50 fb $^{-1}$ ) 500 fb $^{-1}$							
search		I		II		III	
$5\sqrt{N_{bg}}$		(21)	66	(60)	189	(375)	1186
states	$B_{eq}$	mass reach in GeV					
$-1/3\tilde{S}_0$	$2/3$	(318)	332	( $\diamond$ )	<b>311</b>	( $\diamond$ )	$\diamond$
	$1/2$	(289)	<b>323</b>	( $\diamond$ )	<b>309</b>	( $\diamond$ )	$\diamond$
	1	(350)	362	(-)	-	(-)	-
$-4/3\tilde{S}_0$	1	(387)	391	(-)	-	(-)	-
$2/3\tilde{S}_1$	0	(-)	-	(-)	-	(275)	302
$-1/3\tilde{S}_1$	$1/2$	(289)	<b>323</b>	( $\diamond$ )	<b>311</b>	( $\diamond$ )	$\diamond$
$-4/3\tilde{S}_1$	1	(389)	396	(-)	-	(-)	-
$-2/3\tilde{S}_{1/2}$	$1/2$	(369)	385	(359)	377	( $\diamond$ )	<b>308</b>
	0	(-)	-	(-)	-	(239)	<b>287</b>
	1	(384)	394	(-)	-	(-)	-
$-5/3\tilde{S}_{1/2}$	1	(389)	396	(-)	-	(-)	-
$1/3\tilde{\tilde{S}}_{1/2}$	0	(-)	-	(-)	-	(146)	<b>198</b>
$-2/3\tilde{\tilde{S}}_{1/2}$	1	(379)	396	(-)	-	(-)	-
$-1/3\tilde{V}_{1/2}$	$1/2$	(385)	396	(380)	392	(266)	bf 302
	0	(-)	-	(-)	-	(326)	345
	1	(392)	396	(-)	-	(-)	-
$-4/3\tilde{V}_{1/2}$	1	(395)	395	(-)	-	(-)	-
$2/3\tilde{\tilde{V}}_{1/2}$	0	(-)	-	(-)	-	(326)	345
$-1/3\tilde{\tilde{V}}_{1/2}$	1	(390)	392	(-)	-	(-)	-
$-2/3\tilde{V}_0$	$2/3$	(385)	392	(373)	389	(200)	<b>279</b>
	$1/2$	(380)	392	(376)	390	(244)	<b>317</b>
	1	(390)	392	(-)	-	(-)	-
$-5/3\tilde{\tilde{V}}_0$	1	(396)	397	(-)	-	(-)	-
$1/3\tilde{V}_1$	0	(-)	-	(-)	-	(352)	376
$-2/3\tilde{V}_1$	$1/2$	(380)	392	(375)	390	(244)	<b>317</b>
$-5/3\tilde{V}_1$	$1/2$	(396)	395	(-)	-	(-)	-

Table 2: Number of signal events required for a  $5\sigma$  effect in channel I to III and corresponding mass reach in GeV for all leptoquark states classified in Ref. 3 and for the cuts described in the text. Significant gain due to luminosity is emphasized by boldfaced numbers.  $B_{eq}$  denotes the LQ branching ratio into a charged lepton plus jet. Search channels not accessible are marked by a dash, sensitivity limits below 100 GeV by a diamond.

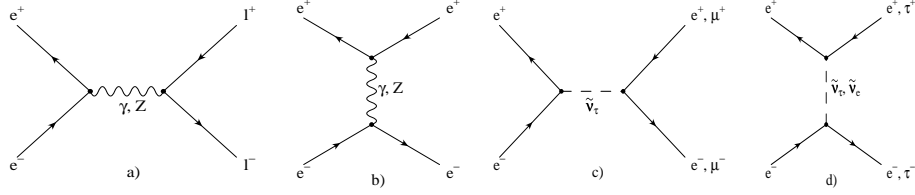


Figure 2: Lowest order contributions to  $e^+e^- \rightarrow l^+l^-$  including sneutrino exchange.

In order to illustrate the size of the deviations from the standard model predictions at future linear colliders we extrapolate the study of Ref. <sup>2</sup> from LEP2 to LC energies. The result is shown in Fig. 3 for  $R$ -parity violating couplings  $\lambda_{i3k}$  respecting the present experimental bounds <sup>9</sup>. As can be seen, the effects (which scale roughly with  $(\lambda/m_{LQ})^2$ ) are of the order of 1% and smaller, except within a mass range of  $\pm 250(750)$  GeV of the  $s$ -channel resonance in  $e^+e^- \rightarrow \mu^+\mu^- (e^+e^-)$ .

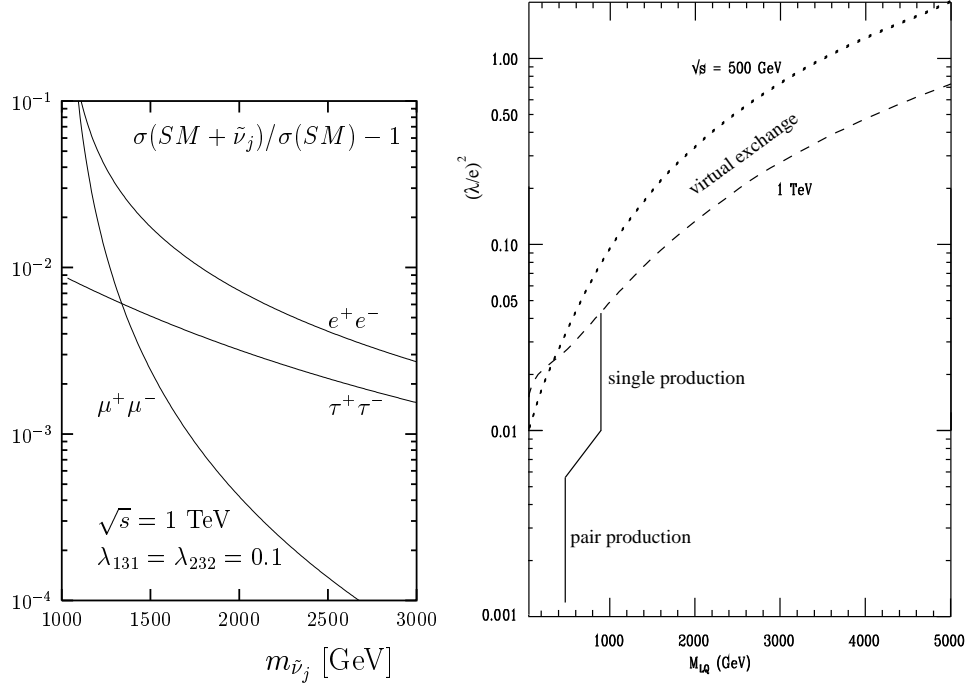


Figure 3: Virtual effects from sneutrino exchange in  $e^+e^- \rightarrow l^+l^-$ .

Figure 4: LQ search limits at linear  $e^+e^-$  colliders. The boundaries for virtual LQ exchange are taken from Ref. <sup>10</sup>.

#### 4 Summary

The search limits for leptoquarks in pair production estimated in this study are independent of the size of the Yukawa couplings  $\lambda$ , but they depend somewhat on the LQ quantum numbers. In many cases, the kinematic limit  $m_{LQ} = \sqrt{s}/2$

is reached within a few percent. In contrast, in single production one can probe the existence of leptoquarks with masses roughly two times bigger than in pair production, however, single production requires sizeable Yukawa couplings. If the latter couplings are large enough, virtual LQ exchange will lead to observable effects in the total hadronic cross section for LQ masses even far beyond the total c.m.s energy. The complementarity of the above reactions is illustrated in Fig. 4.

There is also very useful complementarity of searches in  $e^+e^-$ ,  $pp$  ( $\bar{p}p$ ), and  $ep$  collisions. Firstly,  $e^+e^-$  and  $pp$  ( $\bar{p}p$ ) primarily probe LQ gauge couplings, whereas  $ep$  probes Yukawa couplings. Secondly, while in hadronic collisions leptoquarks being colour triplets are produced democratically, in  $e^+e^-$  collisions one has a hierarchy of production rates reflecting the electroweak and spin quantum numbers. Finally, a very clean and flexible environment for the determination of LQ properties is provided by  $e^+e^-$  collisions. Particularly powerful tools are angular distributions testing spin and Yukawa couplings, and beam polarisation discriminating between different chiralities of the latter. The issues of mass reconstruction, measurement of Yukawa couplings, and determination of spin, weak isospin, etc. are discussed in Ref. <sup>1</sup> where also some illustrative distributions are shown.

Concerning the effects from virtual sneutrino exchange in  $e^+e^- \rightarrow l^+l^-$ , one finds that the existing experimental constraints on  $R$ -parity violating couplings still allow for large deviations from the standard model expectations. In particular, the occurrence of a  $s$ -channel resonance in the LC energy range is a spectacular possibility to look for.

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